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Finite element analysis simulations of thermomechanical head-disk interface contact in thermal flying-height control slider design

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ABSTRACT

In order to achieve higher recording density in hard disk drive (HDD), thermal flying-height control (TFC) slider design has been used to reduce the physical spacing between the read/write elements in the slider and the rotating disk surface. During the read/write operation in hard disk drives, the intermittent contact at the head-disk interface (HDI) directly affects its performance and reliability. In this study, the thermomechanical micro-contact between a TFC slider and a disk defect was systematically investigated through finite element analysis (FEA) modeling and simulations. The thermal actuation technology in a TFC slider was incorporated into the FEA model to enable the thermal protrusion of read/write sensors outward the air bearing surface (ABS). In order to obtain the scientific relationship between the thermal protrusion and the resulting HDI contact behavior, parametric FEA simulations were carried out based on the 2^3-factorial design of experiment (DOE), where the surface temperature rise and the residual deformation on the TFC slider surface were used as the output parameters. From the statistical data analysis, it could be found that the larger thermal protrusion resulted in higher temperature rise and more residual deformation.

1. Introduction

To achieve higher recording density in hard disk drive (HDD), it is required to reduce the physical spacing between the read/write elements in the slider and the rotating disk surface. Researchers have tried to apply the piezoelectric actuation technology into the slider design to control the active flying height [1–5]. However, its complicated fabrication process [2,3] and the high operating temperature [6] prevented the mass production of the piezoelectric actuation slider. As an alternative solution, the thermal actuation technology was newly developed to control the head-media-spacing (HMS) adaptively [7], where a micro-heater in a slider manages the amount of thermal expansion of read/write elements outward the air bearing surface (ABS). A slider including this thermal actuation technology is typically called a thermal flying-height control (TFC) slider [8–11]. Compared to the piezoelectric actuation technology, it has simpler fabrication process with lower manufacturing cost, which enabled it to be successfully implemented into the actual HDD design.

Considering the active HMS of current HDD products is controlled to be a few nanometers through the thermal actuation technology, the head disk interface (HDI) can have intermittent micro-contacts during read/write operation. The high speed HDI contact gives rise to both mechanical stress and frictional heating on the contacting surfaces which can cause critical HDI failures. To further understand the mechanism of material degradation in relation to contact stress and temperature and thereby improve the slider design, researchers have investigated the thermomechanical contact behavior of solids using both computational and experimental methods. Chen and Wang developed a three-dimensional thermoelastoplastic sliding contact model for spherical bodies, from which they investigated the effects of sliding speed, heat partition, and thermal softening of materials on the contact behavior [12]. Coulibaly et al. developed an analytical model to study the thermomechanical coupling of rough surface high speed sliding contact of steel, and the model could well predict the average thermal response, heat flux distribution, temperature profile, and local shear stress field [13]. In addition, using an improved micro-contact model that takes account of substrate deformation and asperity interactions during surface contact [14,15], Lee et al. have developed and proposed a novel thermomechanical contact model, which can provide the spatial distribution of in-situ stress and frictional temperature rise on the contacting bodies [16,17]. From the simulations results of HDI sliding contact, it was observed that the surface temperature rise by frictional heat generation was high enough to initiate the thermal degradation (graphitization or thermal softening) of head DLC film. Accordingly, once experiencing the thermal degradation

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by high speed surface contact, the degraded head DLC film could be easily worn out by the following surface contact. To verify the atomic structure change of head DLC film during HDI contact, micro-Raman measurement has been performed on the slider sample after HDD level test [18]. It was found that the burnishing wear area on the head DLC film clearly showed the increase of sp^2-to-sp^3 ratio and larger size of sp^2 clusters, which indicates significant graphitization process on the head DLC film. Shi et al. investigated thermomechanical contacts between an elastic–plastic sphere and a rigid flat at different sliding speed, and it was found that both sliding friction coefficient and friction stress are significantly dependent on sliding speed while the maximum static friction coefficient is independent of sliding speed [19].

When HDI contact is investigated, finite element analysis (FEA) can also be a useful tool to estimate the in-situ stress and material deformation. In early stage of FEA research on thermomechanical HDI failures, for the convenient of analysis, normal contact without sliding was applied to analyze the plastic deformation on the coating and underlying magnetic layers [20]. Then, to obtain more realistic contact solutions, both normal and sliding motions were applied into the FEA modeling, which enabled to measure the surface flash temperature as well as mechanical stress and deformation [21,22]. Recently, Song et al. have performed an advanced FEA modeling and simulation to examine the thermomechanical contact between disk asperity and TFC slider, where the material temperature rise, plastic strain, and scratch depth/width were measured at different flying height condition [23,24]. In their FEA study, the TFC slider was modeled using the effective material properties based on the surface DLC coating and the underlying substrates, while the initial temperature was selectively applied depending on the substrate materials due to the thermal actuation technology [25]. All of these researches using simplified modeling of slider and asperity contact provided understanding in the contacts that occur at HDI, and helped improve the slider design. In spite of their outstanding modeling and simulation results, there would be some more technical points to improve the thermomechanical HDI analysis.

Based on the actual mechanism of thermal actuation technology in a slider, a micro-heater can provide considerable heat flux to the read/write elements and the other head substrate materials. The closer to the micro-heater would have the higher material temperature. Accordingly, the initial temperature of the material in a TFC slider needs to be given as a function of distance from the micro-heater. In addition, when the read/write elements area is thermally protruded outward the slider surface, it can generate film stress on the head DLC coating. Depending on the amount of the thermal protrusion and the coating thickness, such predetermined film stress could be critical to the HDI contact reliability. To get more physical insights into the thermomechanical HDI contact behavior, these two technical points were addressed in this paper. In the proposed FEA modeling, an effective heat flux was applied to the slider to generate the target thermal protrusion and the relevant DLC temperature. Using the three design factors (i.e., magnitude of thermal protrusion, sliding speed, and DLC thickness), parametric FEA simulation was performed based on the 2^3-factorial DOE, where the surface temperature rise and the residual deformation of the slider surface were used as the output parameters.

2. Methods

In this study, 3-dimensional FEA modeling and simulation have been performed using the explicit solver (Dynamic, Displacement–Temperature) in ABAQUS, which enables to investigate the thermomechanical surface damage of slider during HDI contact.

2.1. Slider and disk defect: materials and geometrical parameters

Fig. 1 depicts the slider and the disk defect used in the FEA model including their geometrical parameters. A simplified slider was used with the dimension of length = 2.5 µm, height = 2.5 µm, and thickness = 1 µm. As shown in Fig. 1(a), based on actual material design in HDD, the slider was made of three different substrates (i.e., AlTiC, Al_2O_3, and NiFe), on which DLC overcoat was applied. It is noted that the length of each substrate material is not the same as actual slider, whose value was simply selected to examine the effects of substrate materials on the resulting contact performance of the slider. For the case of disk defect in Fig. 1(b), the hemi-spherical defect with the radius of 200 nm and the height of 13 nm was made of Al_2O_3, because it is known as one of the embedded defect materials in HDD [26]. This nanometer size particle was placed on top of the magnetic substrate made of CoCrPt which is the major magnetic material of disk. In FEA, to avoid the critical errors from boundary conditions, the height of the slider and disk substrate was much larger than the contact size. Table 1 shows the mechanical and thermal properties of materials used in this FEA model [18,21]. It is known that material properties are usually dependent on temperature. However, due to the unavailability of the temperature-dependent properties for the materials of head and disk, it was assumed that the material properties in this FEA simulation are constant for all temperatures.

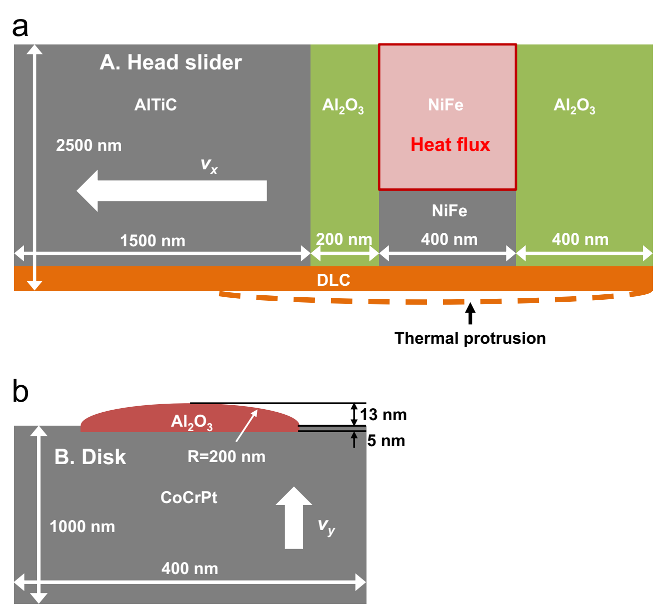

Fig. 1. Schematic of the slider and disk defect used in FEA modeling and simulation, a) Slider with three different substrates and DLC overcoat, b) Spherical disk defect placed on magnetic materials. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Mechanical and thermal material properties.

	NiFe	DLC	AlTiC	Al_2O_3	CoCrPt
Density (kg/m^3)	8120	2150	4250	3970	8900
Young's modulus (GPa)	110	168	410	380	130
Poisson's ratio	0.3	0.3	0.3	0.25	0.3
Yield stress (GPa)	1.7	5	6.86	5.5	2.67
Conductivity (W/m K)	15	0.52	20	1.5	6.03
Specific heat (J/kg K)	500	500	200	775	411
Thermal expansion (10^{-6}/K)	12	6.95	5	5.5	12.5